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Original communication

Experimental penetration of fragment simulating projectiles into porcine tissues compared with simulants

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ABSTRACT

Introduction: Ballistic gelatin is well validated in its ability to simulate the retardation of bullets into homogenous muscle. However the relationship is less clear for fragmentation projectiles and non-homogenous tissues as would truly be found in a human.
Method: 0.16 g, 1.10 g and 2.84 g NATO standardised cylindrical Fragment Simulating Projectiles (FSPs) were fired at a range of velocities (112–1652 m s^{-1}) into four body areas (thigh, abdomen, thorax or neck) of six pig cadavers as well as 20% gelatin. Cadavers were imaged by Computed Tomography (CT) scanning and FSP Depth of Penetration (DoP) ascertained through radiology followed by dissection by a forensic pathologist.
Results: 106/149 (71%) FSPs were retained in tissues enabling DoP measurements and 43/149 (29%) exited the subjects. There was significantly less retardation of FSPs in the thorax and abdomen compared to gelatin but no difference in retardation in leg and neck tissue compared to gelatin. Although the gradient appeared identical for the 2.84 g FSP as well, there were insufficient FSPs retained in the neck and leg for meaningful analysis to be undertaken.
Discussion: Porcine leg and neck muscle was demonstrated to be comparable to 20% ballistic gelatin in terms of retardation, validating the use of projectile penetration algorithms derived from this tissue simulant. The effect of pig skin was significant for the 0.16 g FSP, especially at lower velocities, and we would therefore suggest that specific algorithms for any future numerical injury models be based directly from animal data or validated skin simulants for this smaller sized FSP. Reproducing the retardation effects of FSPs in the thorax and abdomen using tissue simulants alone will be problematic due to the anatomical complexity as well as multiple tissue–air interfaces and we would recommend further research in this area.

1. Introduction

Explosively propelled fragments, such as those produced by Improvised Explosive Devices (IEDs), are the most common cause of injury sustained by military personnel in current conflicts.[1] Injury models are important in simulating the effect that these projectiles have on penetrating human tissues so that methods of potentially mitigating against these injuries can be devised.[1] Animals have traditionally been used as substitutes for humans in ballistics testing, with porcine tissue being the most common, due to both its availability and a belief that the retardation of bullets in porcine muscle is comparable to that of human.[2–4] The use of animal models has understandable ethical implications and therefore there is a desire to develop numerical models to reduce animal testing. However these numerical models require original experimental values from which to inform the material properties from which they are based.

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Tissue simulants were developed in an attempt to negate the requirement for animal models, with ballistic gelatin being the most widely used.[5,6] Ballistic gelatin has been well validated in terms of the retardation of bullets in porcine muscle,[5,7] but the relationship is less clearly defined for FSPs[7,8] in the published literature. With the exception of a single paper that fired a 0.20 g cylindrical FSP into pig skin and muscle,[3] all the experimental data to date has been performed using spheres.[2,7] Although spheres produce greater reproducibility in results due to their regular shape, cylinders would be expected to be more representative of the heterogeneous random explosive fragments produced by IEDs.[8,9]

The objective of this study was to compare the retardation effects of representative FSPs travelling through pig skin and muscle, compared to previous ballistic gelatin firings, which could potentially be used to develop new tissue simulants or to modify the constituents of existing simulants.

2. Method

0.16 g, 1.10 g and 2.84 g NATO standardised[10] cylindrical Fragment Simulating Projectiles (FSPs) were fired at a range of velocities (112–1652 m s^{-1}) into four body areas (thigh, abdomen, thorax or neck) of six pigs, weighing between 45 and 55 kg (killed by a Schedule 1 method). The animals were killed humanely using a Schedule 1 method in the same location as testing occurred and the cadavers were whole and not altered post-mortem. The neck and thigh areas were chosen, as they are mainly composed of skin and muscle. The 1.10 g FSP was chosen, as it is an industry standard mass for the appraisal of body armour.[11,12] The 0.16 g FSP is representative of the most common size of modern pre-formed fragmenting munitions.[13]

The whole animal cadavers were placed on their back on a trolley in front of the firing rig using a stand and clamp to raise the limbs for leg shots. A pressurised cartridge system was used to fire the FSPs through a smooth bore barrel at low velocities and a 7.62 mm rifled barrel and pyrotechnic propellant was used to fire the FSPs at higher velocities with a sabot to allow firing of the 1.10 g and 0.16 g fragments. Velocity was measured using solid-state velocity equipment with a one-metre separation between the sensor heads. Firing commenced within 30 min post-mortem. Subjects were imaged with a Philips Brilliance 16 slice CT scanner within 15 min of completion of firing and a consultant radiologist measured Depth of Penetration (DoP). A forensic pathologist ascertained the DoP within 45 min of completion of firing, measuring by dissection along the wound track from the front (presenting) face of the projectile to the skin surface (or point where skin would have been) along the wound track (Fig. 1). DoP was determined using the value obtained from clinical dissection when the retained FSP could be found and a clear wound track to skin surface measured. For the remaining FSPs the DoP value used was that derived from CT. The DoP for all retained FSPs that hit bone at any point along the wound track or any FSP found immediately beneath the contralateral skin surface was discounted. When a Permanent Wound Cavity (PWC) was visible radiologically (seen as a discrete area of gas within tissue caught in the path of the projectile), its maximum diameter was measured perpendicular to the wound track direction.

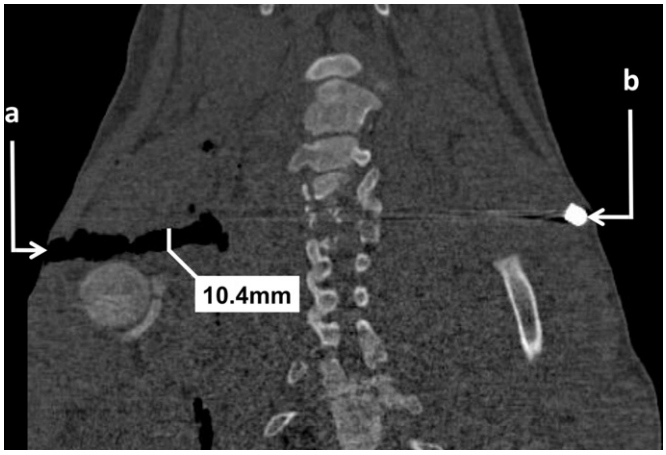

Fig. 1. Coronal reformatted CT viewed using a bone window. Depth of Penetration is determined as the distance between points a and b. The measurement indicates the width of the Permanent Wound Cavity at this point.

Linear regression analysis was used to determine the line of best fit for velocity versus DoP for each sized FSP in each body region. The intercept (velocity required for perforation) and gradient of the linear regression lines for gelatin was compared to see if they were statistically different from those of the animal. Should insufficient points be produced for the regression line to intersect the velocity axis, analysis was undertaken on a line produced by extrapolation until intersect was achieved. The correlation coefficient (R^2 value) was determined for each dataset to demonstrate the 'goodness of fit' of each regression line. Statistical analysis was undertaken with a Chi-squared test and significance defined as a p value of <0.05. To enable comparisons between the DoP produced by different sizes of FSP, the DoP was 'normalised' by dividing the DoP by the projectile diameter.

Type A ballistic grade (250 bloom) 20% by mass dry gelatin powder was mixed with distilled water at 70 ± 5 °C. The water was stirred whilst the gelatin flakes were added slowly. When all gelatin had been added, it was stirred for an additional five minutes, covered and allowed to stand for five minutes. After this, it was stirred once more for 5 min, and then allowed to stand for a further 45 min. Any excess foam that had formed on the surface of the gelatin was scraped off and the liquid gelatin decanted into moulds. Following cooling to 20 °C the gelatin block was removed from the mould and stored at a temperature of 10 °C ± 2 °C for 8–12 h. Fragments were fired into the gelatin and DoP measured by probe.

3. Results

149 FSPs were fired into four body areas; of which 106 (71%) were retained in tissues and DoP measured, and 43 (29%) exited the subject. All 106 retained FSPs could be identified using CT but only 79/106 (75%) retained FSPs could be found by dissection. 14/106 (13%) of FSPs hit bone along the wound track, and these results were excluded from further analysis. Of the 92 retained FSPs that did not hit bone, 59/92 (64%) were identified on surgical dissection and DoP measured. Of the remaining 33/92 (36%), 30/92 (33%) could be identified on CT and DoP determined. For 3/92 (3%) there was no clear wound tract that could be determined by either dissection or CT and these results were also excluded from further analysis.

Results for DoP versus velocity for the FSPs into porcine tissues and gelatin can be seen in Figs. 2–4. R^2 values produced using linear regression lines for velocity versus DoP into gelatin for the 0.16 g, 1.10 g and 2.84 g FSPs were 0.94, 0.95 and 0.97 respectively. R^2 values of the regression lines for velocity versus DoP for the four animal body areas are displayed in Table 1. Extrapolation of the line of best fit for the 0.16 g and 1.10 g FSPs into leg tissue gave threshold perforation velocities for skin of 147.6 m s^{-1} and 77.6 m s^{-1} respectively.

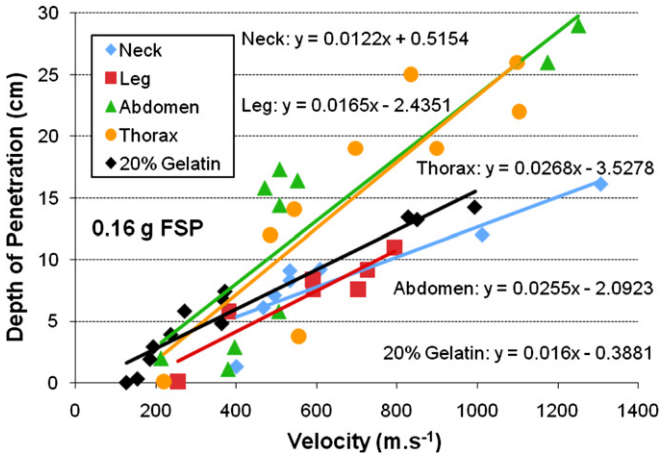

Fig. 2. Depth of Penetration versus velocity for 0.16 g FSP.

Statistical significance between gelatin and porcine tissue for the intercept (estimated velocity required to perforate tissue) and the gradient (ease of projectile passage through tissues) are demonstrated in Table 1. Only 1/8 (13%) of 2.84 g FSPs fired at the leg and 4/14 (29%) of the same mass fired at the neck were retained; these numbers were too small for statistical significance to be determined. Values for normalised DoP in the gelatin for all the FSPs showed an excellent correlation to velocity as well as those values derived from firings into the neck and leg using polynomial curves (Fig. 5). Values for FSPs derived from firings into the abdomen and thorax showed far worse correlation. A visible PWC was only produced by the 2.84 g FSP and only in the neck or leg. The maximum permanent cavity diameter varied between 6 and 14 mm at impact velocities of 451–1312 m s^{-1}.

4. Discussion

The objective of this study was to compare the retardation of NATO standardised FSPs into 20% ballistic gelatin compared to four body areas of a porcine model as well as providing evidence for the velocity required for skin perforation. There was no statistical difference in the velocity required for skin perforation compared to gelatin surface perforation for either the 1.10 g or 2.84 g FSPs. A significantly greater impact velocity was required for the 0.16 g FSP to perforate porcine skin and muscle compared to gelatin. This perforation velocity for porcine skin was also higher than would be expected from the closest available experiments using skin from

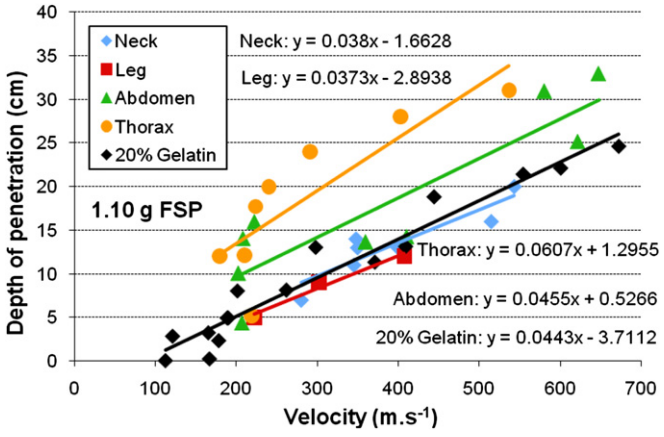

Fig. 3. Depth of Penetration versus velocity for 1.10 g FSP.

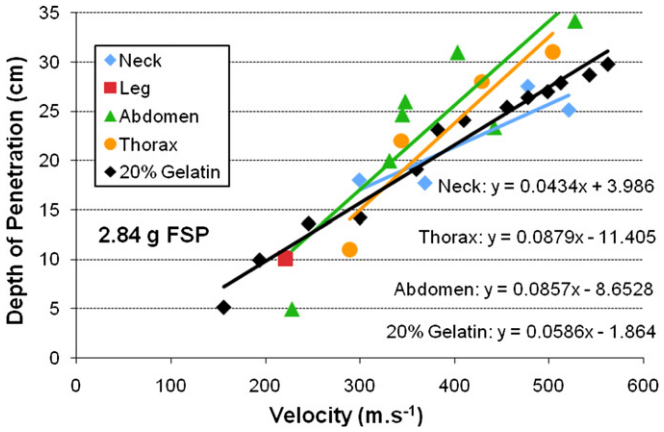

Fig. 4. Depth of Penetration versus velocity for 2.84 g FSP.

Post-Mortem Human Subjects (PMHS),[11] demonstrating the importance of skin in the retardation of smaller masses of FSPs, especially at lower velocities. This should be taken into account in any relevant numerical models.

The gradients of the regression lines for the 0.16 g and 1.10 g FSPs were identical to one another in the neck, leg and in gelatin, reflecting that gelatin appears to be a suitable simulant of porcine muscle (from which both body areas are primarily composed of) for fragments as well as bullets. Due to the legs and neck having less tissue length for FSPs to travel through, it was difficult to achieve retardation of the 2.84 g FSP, even at lower velocities. It is therefore not possible to categorically state that gelatin is a suitable simulant for muscle in terms of the retardation of a cylindrical 2.84 g FSP, despite the gradient graphically appearing very similar. However by plotting normalised DoP versus velocity for gelatin (Fig. 5), it was clear that the 2.84 g FSP followed the trend produced by the other two FSPs. We therefore believe that gelatin is a valid model for animal muscle for NATO standardised cylindrical FSPs between 0.16 g and 2.84 g.

Comparisons of the DoP produced by the 0.16 g cylindrical FSP in our experiment to the only comparable experimental data in the open literature[3] (which used a 0.20 g cylindrical FSP) demonstrated almost identical DoP versus velocity for porcine tissue. However their results of penetration into 20% gelatin were different from ours. This may reflect that these authors mixed their 20% gelatin at 20 °C compared to 10 °C used in our study, which can have significant effects on the retardation of projectiles.[6,14] Such differences in experimental results have led to recommendations regarding standardisation and calibration of gelatin preparation between institutions[12,13] and we would like to reinforce the importance of

Table 1
Significance of results of tissue penetration compared to 20% gelatin.

Fragment simulating projectile specifications	Mass (g)		0.16	1.10	2.84
	Length (mm)		3.7	6.4	8.2
	Presented diameter (mm)		2.7	5.4	7.5
Was a statistically significant difference found from that of 20% gelatine?	Neck	Gradient	No	No	No
		Intercept	Yes	No	N/A
		R^2 value	0.80	0.83	0.78
	Leg	Gradient	No	No	N/A
		Intercept	Yes	No	N/A
		R^2 value	0.86	1.0	N/A
	Abdomen	Gradient	Yes	Yes	Yes
		Intercept	Yes	No	N/A
		R^2 value	0.76	0.80	0.78
	Thorax	Gradient	Yes	Yes	Yes
		Intercept	Yes	No	N/A
		R^2 value	0.77	0.71	0.89

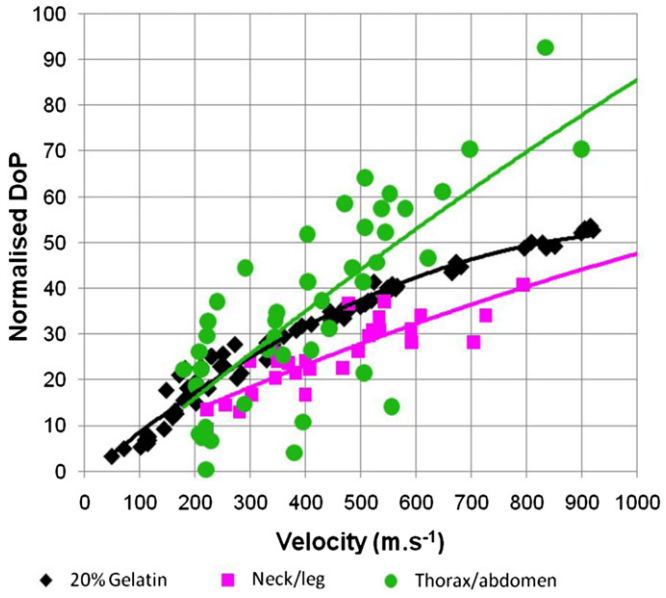

Fig. 5. Normalised DoP into 20% gelatin versus velocity for all three fragment sizes.

clearly describing this part of the methodology in any future reports.

As would be expected the FSPs travelling through the thorax and abdomen showed significantly less retardation than those through leg and neck, reflecting passage of the projectile through air containing organs instead of just muscle. It will clearly be very difficult to model the retardation effects of these tissues due to their anatomical complexity and consideration should be made to either the construction of new tissue simulants or modifications of existing ones (such as gelatin of a lower concentration). Alternatively it has been suggested that a conversion factor could be used to make any results more appropriate to individual tissues.[15] Due to considerable differences between animal and human anatomy in the thorax and abdomen, it may be that future experimental testing utilising the thoracic and abdominal areas of a PMHS model would be more appropriate and we would recommend that such trials are undertaken.

In conclusion our trial has demonstrated that 20% gelatin is a suitable tissue simulant for modelling the penetration of pig skin and muscle for FSPs of masses between 0.16 g and 1.10 g. This model also appeared valid with masses up to 2.84 g but the results were not statistically significant. The effect of pig skin on the retardation of the 0.16 g FSP became significant at lower velocities and we would therefore recommended that algorithms for such perforations be based directly from animal data or from gelatin backed by a validated skin simulant. 20% gelatin alone is not suitable for simulating perforations of FSPs into animal tissues not mainly composed of muscle such as the abdomen or thorax. Although conversion factors may allow some predictions to be made, should the perforation of human non-muscle containing areas by FSPs be required, then testing on PMHS would potentially be justified. The use of CT in addition to surgical dissection alone enabled more FSPs to be identified and thereby increasing the dataset that could be utilised in this study. Such a synergistic approach also now occurs in post-mortem examinations undertaken on UK service personnel,[16] in which radiological characterisation of wounds (the so called 'virtopsy') is carried out in conjunction with more conventional surgical dissection by a forensic pathologist and their findings combined.

Ethical approval

Animals were killed using a Schedule 1 method in accordance with Ministry of Defence ethical standards for animal research. Ethical approval was kindly granted by the Ministry of Defence Research and Ethics Committee (MoDREC).

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None declared.

Conflict of interest

We the authors can confirm that there are no conflicts of interest known to us and that it has not been submitted elsewhere.

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